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1993 March 9
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Mr. Robert J. Hansen
Scientific Officer
Office Of Naval Research
800 North Quincy Street
Arlington, VA 22217-5000
Attn: RJH, Code:121
Ref: N00014-91-C-0128

SUBJECT: **INTERIM STATUS REPORT AND REQUEST FOR ADDITIONAL FUNDING**

REF: **CONTRACT NO. F33615-92-C-5914; ROLE OF MICROSTRUCTURE ON FATIGUE DURABILITY OF ALUMINUM AIRCRAFT ALLOYS**

Dear Mr. Hansen:

In accordance with CLIN 002, CDRL A001 of the referenced agreement, enclosed is an interim status report comprised of the following attachments:

- Attachment 1 The original contract task schedule
- Attachment 2 Summary of technical progress by task
- Attachment 3 Narrative on the program's progress and direction (This narrative is excerpted from the introductory sections of a comprehensive technical report draft scheduled to be completed 93 April 15)
- Attachment 4 Graph of actual versus budgeted expenditures

As indicated in Attachment 4, through 1993 February, Alcoa has incurred contract expenditures of $376,066 with contract funding currently at $350,000. As stipulated in the limitation of funds clause, FAR 52.232-22, a letter was sent to the Contracting Officer in 1992 August requesting additional funding. Subsequently, during a conversation with the contract specialist in 1992 October, we learned that funding was being withheld until the issuance of the subject interim report. Accordingly, with the submission of this interim report, Alcoa requests that additional funds be obligated to the contract. It is imperative that this funding be obligated as soon as possible to ensure uninterrupted performance.

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In several discussions with the Navy, desire has been expressed in shifting program emphasis to expand the 7050 pore/particle effort at the expense of the Al-Li effort, or in an attempt to reduce program costs simply eliminating the Al-Li work. To date significant effort has been put forth on the Al-Li portion of the program. The expenditures for the Al-Li portion of the work is estimated at $135,000. If all the Al-Li work is stopped, it must be recognized that the Navy will not capture any value from the Al-Li expenditures to date. Alcoa feels that it is essential that the immediate discussions with the Navy be held to establish the program's future, and we are prepared to make suggestions based upon Navy recommendations.

If you require additional technical information or clarification, please contact R. J. Bucci at (412) 337-2671. Contractual matters may be discussed with the undersigned at (412) 337-4038.

Sincerely,

Michael G. Plonsky
Contract Development Specialist
Government Contract Administration
Alcoa Technical Center

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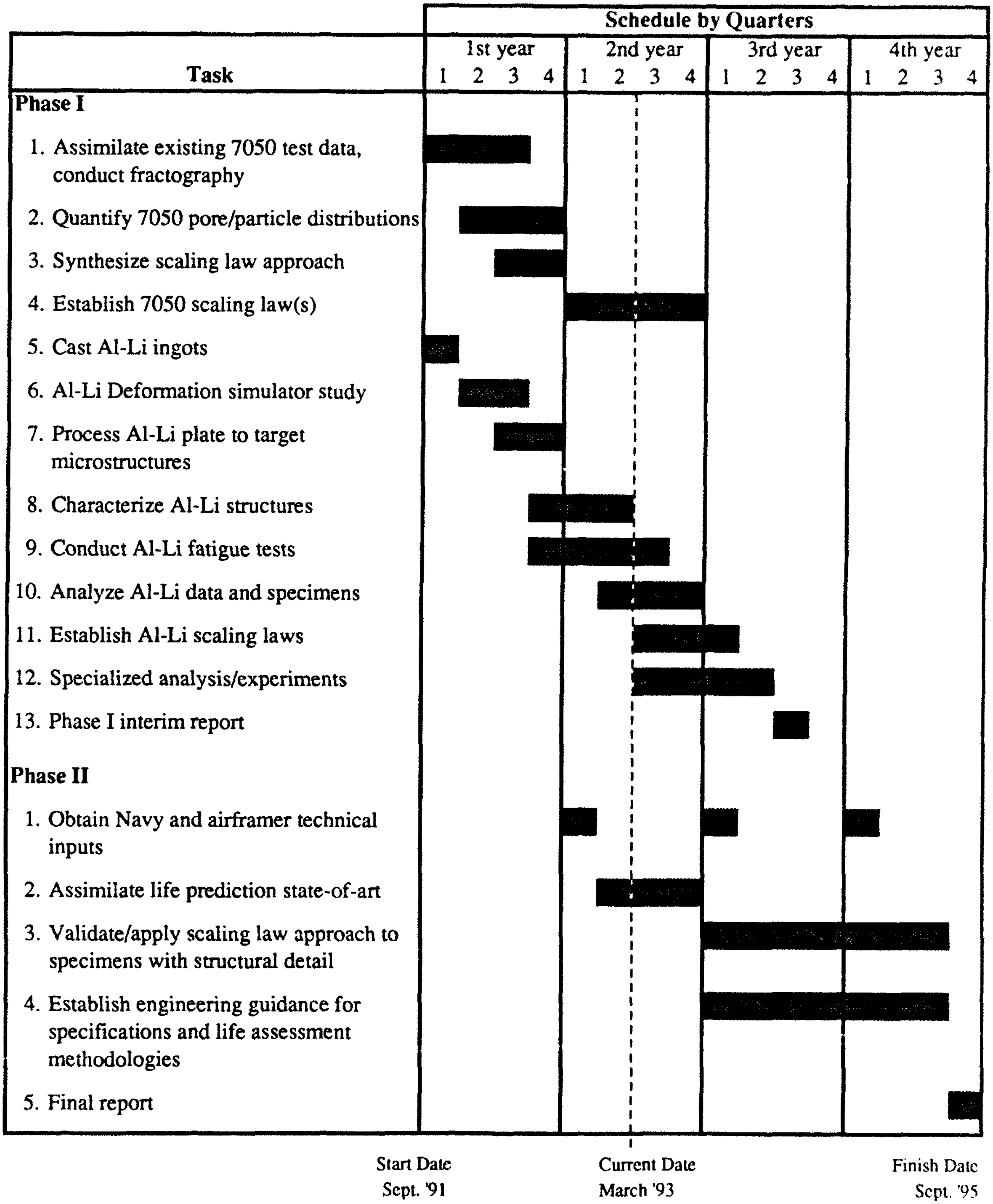
Attachment 1

Original Contract Task Schedule



Attachment 2

Role of Microstructure on Fatigue Durability of Aluminum Aircraft Alloys

Summary of Progress Against Contract Tasks

Phase I	Estimated % Completed
Task 1: Assimilate existing 7050 test data, conduct fractography	*90*

- Alcoa historical 7050 fatigue test data has been assembled and reviewed.
- The range of microstructures examined in the program has been expanded from two in the contract proposal to five. In addition to the old and new quality thick plate, the program includes low porosity thick plate, low particle thick plate, and thin plate. These materials provide a range of microstructures/fatigue failure modes to help understand and model early stage fatigue damage. Though the scope of the program has expanded, the total program cost to the Navy has not changed.
- The fatigue test data on additional microstructural variants of 7050 have been assembled.
- Fractography of failed coupon specimens has been completed. The microstructural features controlling fatigue initiation have been identified.
- Samples of old and new quality plate have been supplied to the UCLA team in support of their ONR program.

Task 2: Quantify 7050 pore/particle distributions — *90*

- The pore/particle distributions which initiate the fatigue failures in the various materials have been quantified.
- The particle distributions on random plane cross-sections have been quantified.

Task 3: Synthesize scaling law approach — *90*

- A scaling law approach has been formulated which includes the application of initiation and growth models in a probabilistic fracture mechanics framework.

Task 4: Establish 7050 scaling law(s) — *75*

- A growth model for fatigue from microstructural inhomogenieties has been applied using the failure causing microstructural features identified in Task 2 as input. The modeling has been extended for open hole as well as smooth fatigue tests.
- A method of scaling the pore/particle distributions observed on random plane sections to the extreme value distributions of failure causing features has been employed.
- Initial work modeling the initiation of fatigue damage from particles has begun.

Task 5: Cast Al-Li ingots — *60*

- An alternate route has been employed to obtain the proposed variants of alloy 8090 plate at no added cost to the program. The materials are obtained using commercially available plate in combination with additional thermomechanical processing.

	Estimated % Completed
Task 6: Al-Li deformation simulator study	-

- This task was to support the original proposed processing route. It has been replaced by the aforementioned processing route.

Task 7: Process Al-Li plate to target — *60*

- Variant 1 has been obtained as commercial plate, 3.2 in. thick.
- Variant 2 has been produced through additional thermomechanical processing of commercial plate.
- The processing of material for variant 3 has been put on hold as a result of verbal communications with the ONR regarding possible changes in the direction of the program.

Task 8: Characterize Al-Li structures — *40*

- The microstructure of variant 1 has been fully characterized. The microstructure consists of thicker un-recrystallized grains
- Microstructural characterization of variant 2 is underway. The microstructure consists of thinner, more elongated un-recrystallized grains with more deformation texture than variant 1.
- Variant 1 has been supplied to the UCLA team for their characterization efforts in support of their ONR program.

Task 9: Conduct Al-Li fatigue tests — *50*

- Smooth and open hole fatigue tests of variant 1 has been completed.
- Smooth fatigue tests of variant 2 are complete, open hole tests are underway.

Task 10: Analyze Al-Li data and specimens — *20*

- Fractography of smooth fatigue failures of variant 1 has been completed. Identification of controlling microstructural features is in progress.
- Fractured ends of fatigue specimens of variant 1 have been supplied to UCLA team.

Task 11: Establish Al-Li scaling laws — *0*

- Not begun yet.

Task 12: Specialized analysis/experiments — *0*

- Not begun yet. To be done as required.

Task 13: Phase I interim report — -

- Original contract called for report at completion of Phase I (end of third year). Per Navy request a detailed Phase I progress report is in preparation.

Task 14: Program management — -

- Interaction and consultation has been maintained with the UCLA team on their concurrent ONR program.

Phase II	**Estimated % Completed**
Task 1: Obtain Navy and airframer technical inputs	*10*
• Participated in Navy program review, August 12-13, 1992 in Washington D.C..	
Task 2: Assimilate life prediction state-of-art	-
• Not begun yet.	
Task 3: Validate/apply scaling law approach to specimens with structural detail	-
• Not begun yet.	
Task 4: Establish engineering guidance for specifications and life assessment metholologies	-
• Not begun yet.	
Task 5: Final Report	-
• Not begun yet.	

Attachment 3

Role of Microstructure on Fatigue Durability of Aluminum Aircraft Alloys*

Executive Summary

The goal of this program is to affect change in metallic aircraft life assessment methodology through quantitative understanding of how material microstructure impacts fatigue durability performance. Various studies have shown that most metal cracking problems encountered in service involve fatigue. Further studies have shown that metallurgical discontinuities and/or manufacturing imperfections often tend to exacerbate such problems by causing cracks to occur sooner than expected. This program concentrates on the initiation and early growth stage of fatigue cracks where the majority of structural life is spent. The program has two general objectives (1) quantifying effect of aluminum alloy microstructure on early stage fatigue damage evolution and growth, and (2) establishing an analytical framework to quantify structural component life benefits attainable through modification of intrinsic material microstructure. The modelling approach taken couples quantitative characterizations of representative material microstructures with concepts of probabilistic fracture mechanics.

Historical fatigue data from Alcoa commercially produced 7050-T7451 plate materials of varying pedigrees is being used to establish a foundation for the subsequent analytical developments. Alloy 7050 is widely used in modern Navy aircraft because of its good balance of strength, toughness and corrosion resisting properties. Additional experimental derivatives of alloy 7050, along with microstructural variants of Al-Li alloy 8090 plate, have also been fabricated and are being examined to broaden the study to include a range of microstructural features which could potentially impact fatigue durability. The technical approach taken in this work is to first quantify the population of crack initiating microstructural features (the extreme value distribution) either analytically or via post test examination, and second to establish fracture mechanics based protocols enabling correlation of these features with coupon fatigue lifetime distributions. The third step will

* This narrative is excerpted from introductory sections of a comprehensive technical progress report draft in preparation.

be to establish methods of scaling the distribution of material microstructural features from random plane microstructural characterization to predict the extreme value distribution of microstructural features (the weak links) causing failure. The final and ultimate goal is to develop modelling capabilities that enable probabilistic component life assessments to be made from the distribution statistics obtained by microstructure characterization. This modelling approach would offer a simpler alternative to expensive fatigue test programs involving large numbers of structural element tests. It would also provide a way to interactively adapt life-cycle analyses into design and problem solving processes.

The current program status is that historical Alcoa fatigue data on alloy 7050 has been assimilated and reviewed. Random cross-sections and specimen fractures have now been obtained and analyzed for the 7050 alloy variants. Models have been synthesized and are being evaluated against the available data. The 8090 modelling work is scheduled to follow that provided by the 7050 experience. To date, two of the three proposed 8090 variants have been fabricated, and the material characterization is underway.

The microstructural variants of alloys 7050 and 8090 in concert with the models in development provide an opportunity to study how changes in microstructure affect lifetimes of structural components. The examination of failed specimens from the variations of the materials employed has identified a hierarchy of microstructural features that are important. In smooth and open hole coupon fatigue tests of the 7050 alloy variants, pores, particles, and grain structure were the features found to exert greatest influence on fatigue performance, generally in that order. However, it was shown that relative magnitude (and even order) of importance within the metallurgical feature hierarchy can shift as conditions of the test (e.g., notch stress concentration and applied loadings) change. Analytical models incorporating microstructural information have been used to explain these effects, and life predictions incorporating these concepts have been shown to correlate well with fatigue results from both smooth and open hole test specimens. The models considered employ fracture mechanics concepts so they can be readily extended to design practice. Existing probabilistic models for the crack growth portion of total life are being used, and an initiation model is being adapted to the predictive scheme. With these models in place a variety of fatigue evaluation scenarios can then be considered.

A vision has been established for exploiting results of this program as a building step towards a material's oriented approach to durability design. Once the microstructural features affecting fatigue have been identified, it follows that life improvement and consistency of performance should be achievable through optimization of material microstructure. A key goal within this program is to illustrate how improved materials should be characterized for use. Potential examples are being developed to show how the analytical concepts and data base being established might be advantageously applied to save weight, extend life, and reduce operator costs. Moreover, though central focus of the work is on intrinsic microstructural inhomogeneities, the quantification of other defect populations (e.g., corrosion pits, manufacturing nicks and dings) and their effects could also be embraced by the philosophy of the approach under investigation. This combination would be valuable for use in design conceptualizations, setting limits of manufacturing quality inspection, and making risk decisions applicable to the aging fleet.

The Problem

Weight and life cycle costs have always been major considerations in design and operation of aircraft. More recently, because of declining defense budgets, there is strong incentive to keep our aging fleets flying well into the next century. For many airplanes within the current inventory, this means an additional 20 to 50 year service extension over that projected at the time of procurement. Unfortunately, these aircraft were not designed for this extended lifetime, and some have been built with materials inferior to those available today. To achieve the new lifetime goals most older airplanes will require some modification to ensure continued safety and economic operation during their extended service. Also, modernization efforts will continue to add weight to existing aircraft systems in the form of more sophisticated weaponry and avioncs. Consequently, there is ample incentive for durable, fatigue resistant, materials that can be used to save weight (raise operating stresses) and/or extend life of metallic airframe parts. For reasons of affordability and supportability, a more durable material which can serve as a direct replacement for its incumbent is highly desirable.

Efficient design and operation of metallic airframes requires analytical tools to evaluate conditions leading to formation and growth of fatigue cracks. Damage tolerance procedures employed to analyze growth of large, inspectable cracks are mature, having their foundation in fracture mechanics theory. In contrast, current practices employed in durability-based evaluations (longevity without appreciable cracking) are largely empirical.

Given time and cyclic loadings of sufficient magnitude, all metallic materials develop crack-like flaws. If allowed to grow uncontrolled, these cracks will eventually affect airframe integrity and operating costs. Generally, the evolution of these flaws is accelerated when microscale inhomogeneities, such as porosity or second phase constituent particles are present to facilitate fatigue initiation. It follows, therefore, that life and consistency of performance should be achievable through metallurgical controls that reduce both the number and severity of potentially harmful material discontinuities. This is particularly true of thick part applications (e.g., bulkheads, lugs, spars, etc.) where the parent metal fabricating constraints (e.g., large ingots, solidification and quenching rates, rolling practices) limit the amount of mechanical work imparted to heal porosity and/or to break-up remnants of the original cast microstructure.

State-of-the-art material selection and procurement practices are not well structured to differentiate product initial fatigue quality (e.g., pores, particles, scratches or other microscale discontinuities that exacerbate cracking problems). This results in lost opportunities for performance and operator cost saving enhancements at affordable costs (e.g., by direct material replacement or tighter manufacturing controls). In most cases the harmful discontinuities in question are too small to be detected reliably, and conventional property tests used in specifications are insensitive to initial fatigue quality. Moreover, quantification of the durability enhancing possibilities through optimization of microstructure is made difficult by the statistical nature of fatigue and the empirical approaches taken by designers.

The USAF has developed a structural durability methodology to deal with effects of initial quality on airframe integrity [1]. The approach characterizes the initial fatigue quality of a material/component and uses probabilistic fracture mechanics to predict the statistics of fatigue cracking originating from inherent defect populations. Despite promise of the methodology, the tools are not widely exploited by industry. This is because little data exists for the inherent material/component fatigue quality, and protocols for generating such information are not well established. Consequently, airframe designers have insufficient confidence to justify the investment of undertaking this new, albeit promising, approach.

In the Air Force protocol, the representation of the material initial fatigue quality combines the effects of both manufacturing and material microstructure. However, microstructure is not directly incorporated into the present day tools. This program is aimed at producing basic understanding and data to incorporate microstructure into the existing framework, and to increase confidence in the methodology, which will eventually lead to broader utilization of the tools. Additionally, exploitation of fatigue improved materials would be facilitated by availability of such a framework capable of connecting microstructure to component performance. Accomplishing these steps would go a long way toward defining the engineering protocols and initial fatigue quality data base needed for technology insertion.

Program Objective

The goal of this program is to provide understanding, representative data and an analytical framework to show that significant fatigue durability improvement is possible through modifications to microstructure. The effort includes establishing data and fracture mechanics based test/evaluation protocols to: (1) link microstructure with fatigue damage evolution and crack growth, and (2) quantify/predict fatigue durability improvements attainable through optimizations of microstructure.

Though the main focus of the work is on developing an analytical capability to study impact of intrinsic microstructural inhomogeneities on fatigue longevity, other extrinsic discontinuity populations (e.g., corrosion pits, scratches, tool marks) and their effects could also be analyzed under the philosophy of the approach.

Approach

The program work scope is built around the following premises:

- Fatigue sensitivity to microstructure is greatest when the damage (cracking) size is on the scale of the governing microstructural features. Early stage cracking (path and propagation rate) is strongly microstructure dependent, but as cracks grow beyond the scale of microstructure, propagation resistance is controlled more so by near-tip plasticity and crack wake (closure) effects. Since the majority of useful fatigue life is spent in propagating to small crack sizes, understanding the mechanisms and statistical nature of microstructure involvement in early stage damage evolution is key to optimization of materials for fatigue durability.

- The durability performance criterion of greatest practical interest to this study is fatigue crack initiation and growth to an inspectable size which may require corrective action. In metallic airframes a 0.05-in flaw represents a typical lower limit for reliable crack detection.

- Quantitative linkages of the following microstructural features to fatigue durability performance are being sought: pores, particles, grain structure, crystallographic texture, slip planarity and precipitate structure. Of these, the first three items have received the greatest attention to date. In addressing the role of these features, a goal is to establish the order of importance relative to fatigue longevity. For example, the classical mechanism for fatigue crack formation and early stage growth is associated with crystallographic slip [2]. This mechanism, however, can be circumvented by initiation at intrinsic material discontinuities such as pores and particles, and is controlled by their size, frequency, and spatial distribution relative to the specimen configuration and loading details.

- The approach being taken in this investigation considers probabilistic fracture mechanics concepts to quantify fatigue damage accumulation originating from or affected by populations of inherent microstructural features (discontinuities). Under this approach, fatigue durability improvement can be quantified under either of the two performance scenarios depicted in Figures 1a and 2a. The first of these quantifies improvement as life distribution to fixed flaw size, while the second representation quantifies improvement as flaw size exceedance after fixed lifetime. Examples of such quantification are shown in Figures 1b and 2b using data obtained from Air Force fatigue tests on two of the 7050 plate microstructural variants [3].

- The schematic illustration of Figure 3 shows three fatigue durability improvement scenarios that are potentially attainable through modification of material microstructure. The first two scenarios , "reduce initial defects" and "reduce crack growth variability", show improvement achieved through quality controls on metal manufacturing processes. The third approach, "increase crack growth resistance", may require alloy modification. In Figure 3 the economic limit represents a flaw size beyond which remedial action will be necessary. The range of microstructure features to be addressed by this program accommodates examination of all three scenarios, however, the first scenario, "reduce initial defects," will serve as the central focus.

- The program objectives require that materials of varying pedigrees (different inhomogeneity populations) be available. One of these materials represents a lowest common denominator that current specifications allow. Other material variants represent improved fatigue quality products. For this purpose the program is relying on extensive Alcoa 7050-T7451 alloy experience. Alloy 7050 was developed specifically for aircraft thick section applications (e.g., bulkheads, lugs, wing spars) requiring good balance of strength, toughness and corrosion resisting properties. Historical Alcoa fatigue test data and analysis have already shown dramatic S-N fatigue improvements through tightening of manufacturing processes to control distributions of pores and particles [4-11]. Test results and failed specimens from 7050 plate materials of varying pedigrees are being made available (at no cost to the Navy) to benchmark performance improvement potential. The Alcoa 7050 results supplement the present program by serving as a foundation for development of analytical protocols. Microstructural characterization along random plane sections of the materials allows for statistical correlation with failure causing features (the weak links).

- The aforementioned Alcoa 7050 plate materials are best suited for study of pore/particle effects. Addition of an aluminum-lithium alloy to the program provides opportunity for expanding the range of microstructure feature variants through control of thermal processes. This is advantageous because more conventional 2xxx or 7xxx aluminum alloys would require multiple compositions (greater expense) to cover the range of microstructural variants possible within the single Al-Li alloy composition. An Al-Li alloy composition similar to that of alloy 8090 is being used. The 5-8% density saving afforded by the Al-Li alloy makes it an attractive addition to the program.

- Durability design methodologies which used the concept of an equivalent flaw size (EIFS) population to quantify initial fatigue quality have been developed. This enables evaluation of structural fatigue performance in probabilistic terms (e.g., Figures 1 and 2). Analytical procedures have been developed to obtain the EIFS population from coupon specimen data [6]. These procedures normally involve back extrapolating crack growth to its origin as shown in Figure 4. This investigation provides opportunity to validate results of these calculations with actual flaw population measurements revealed by post-test fractography. The goal is to establish a protocol for defining an intrinsic material characteristic (e.g., EIFS population) from coupon specimens, which in turn can be input into a probabilistic fracture mechanics scenario to predict consequences on structural performance [12]. An envisioned engineering framework for this computational strategy is shown schematically in Figure 5.

- The statistics of fracture data has been studied for many years [13] with much of the effort devoted to study of extreme value distributions. The idea is that materials contain weakening flaws, and though there is a population of these flaws the failure seeks out the dominant flaw as the weakest link. That is, the total population of flaws is not as important as the distribution of harmful (largest?) flaws, the extreme values. A goal of this study is to explore whether the extreme intrinsic material flaw (or equivalent flaw) population can be defined from random metallographic cross sections. The rationale is to attempt to extract information from metallographic images that can be represented in the same functional form as information extracted from coupon specimen tests. A schematic representation of this logic is shown in Figure 6. The connection of the computer and microscope makes this analysis feasible. Input obtained from images can be digitized and subjected to tessellations and finite element calculations to quantify the localized areas of high strain concentration [14]. If successful this capability will accommodate replacement of large numbers of fatigue tests by representative metallographic characterization. In this way building of the initial fatigue quality data base could be made more cost effective to facilitate broader implementation of the probabilistic fracture mechanics durability design tools.

- The expected outcome of this investigation will be insight into material's fatigue enhancement through microstructural control, coupled with models and procedural guidance for exploitation of improved materials within probabilistic fracture mechanics based durability design rationale.

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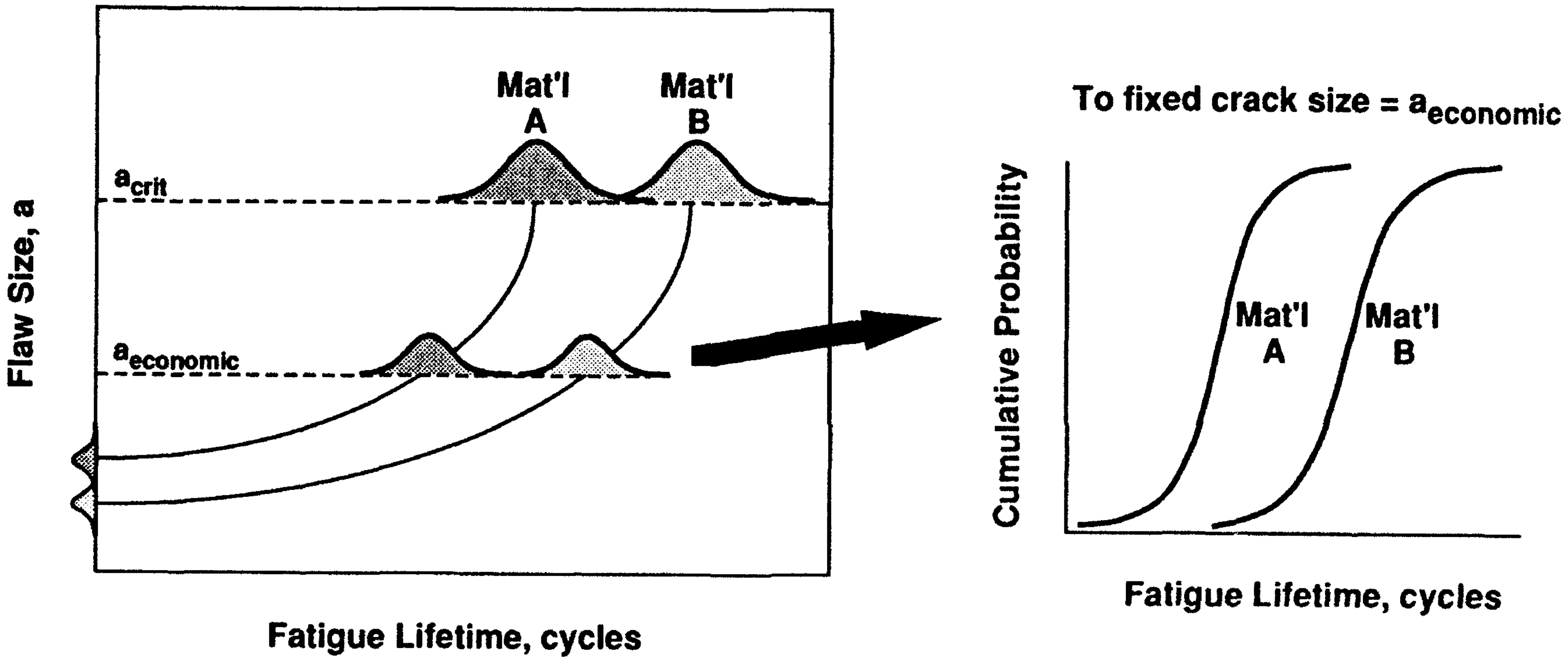

Figure 1a. Schematic representation of the cumulative lifetime distribution to a fixed flaw size for two materials with different intrinsic defect populations.

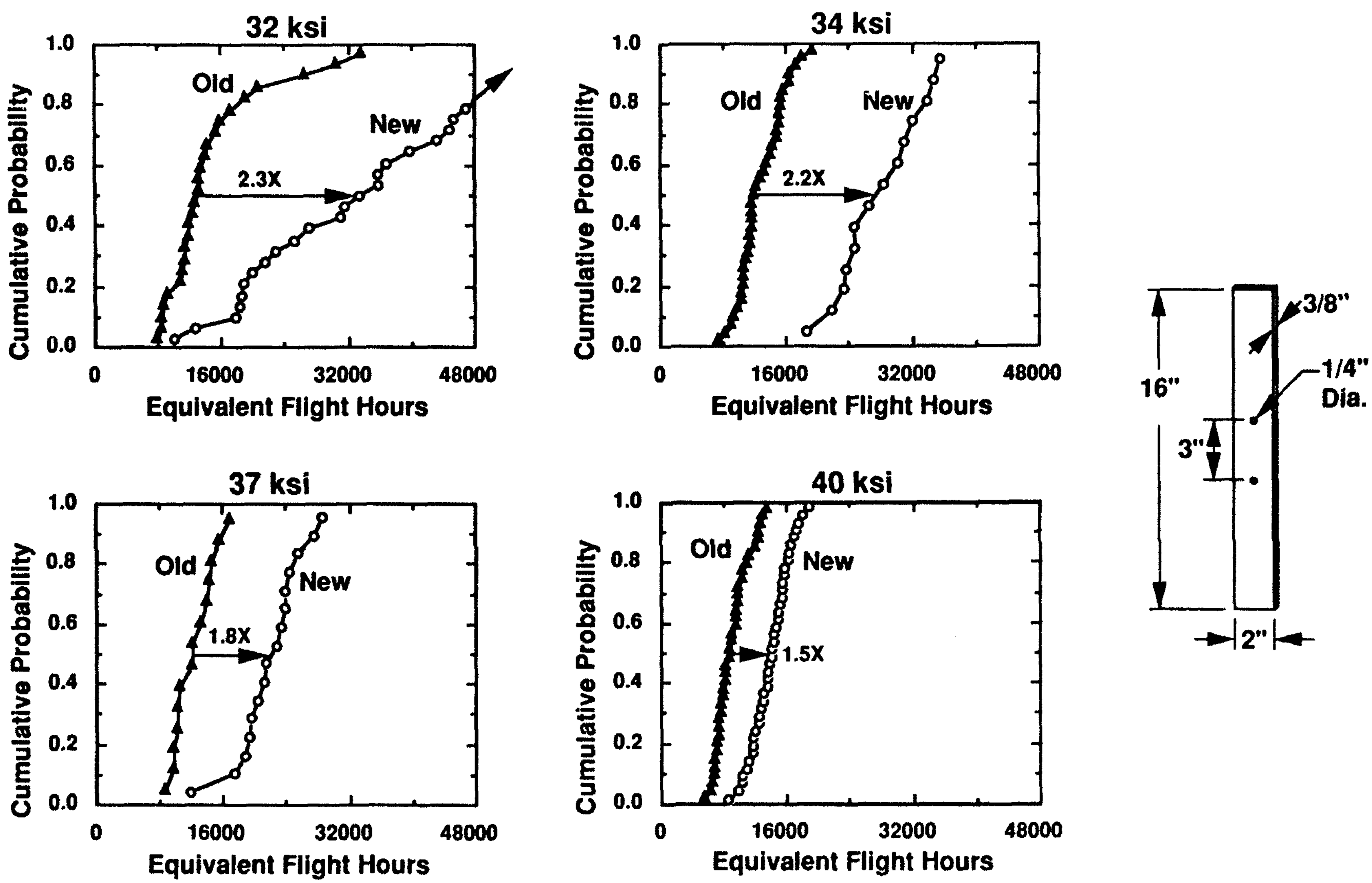

Figure 1b. Effect of 7050-T7451 thick plate quality on cumulative life probability to 0.05 in flaw, T/2 specimen location, LT orientation, F-16 400 hr. lower wing spectrum loading, spectrum peak stresses of 32, 34, 37 and 40 ksi. Test results courtesy of USAF [3].

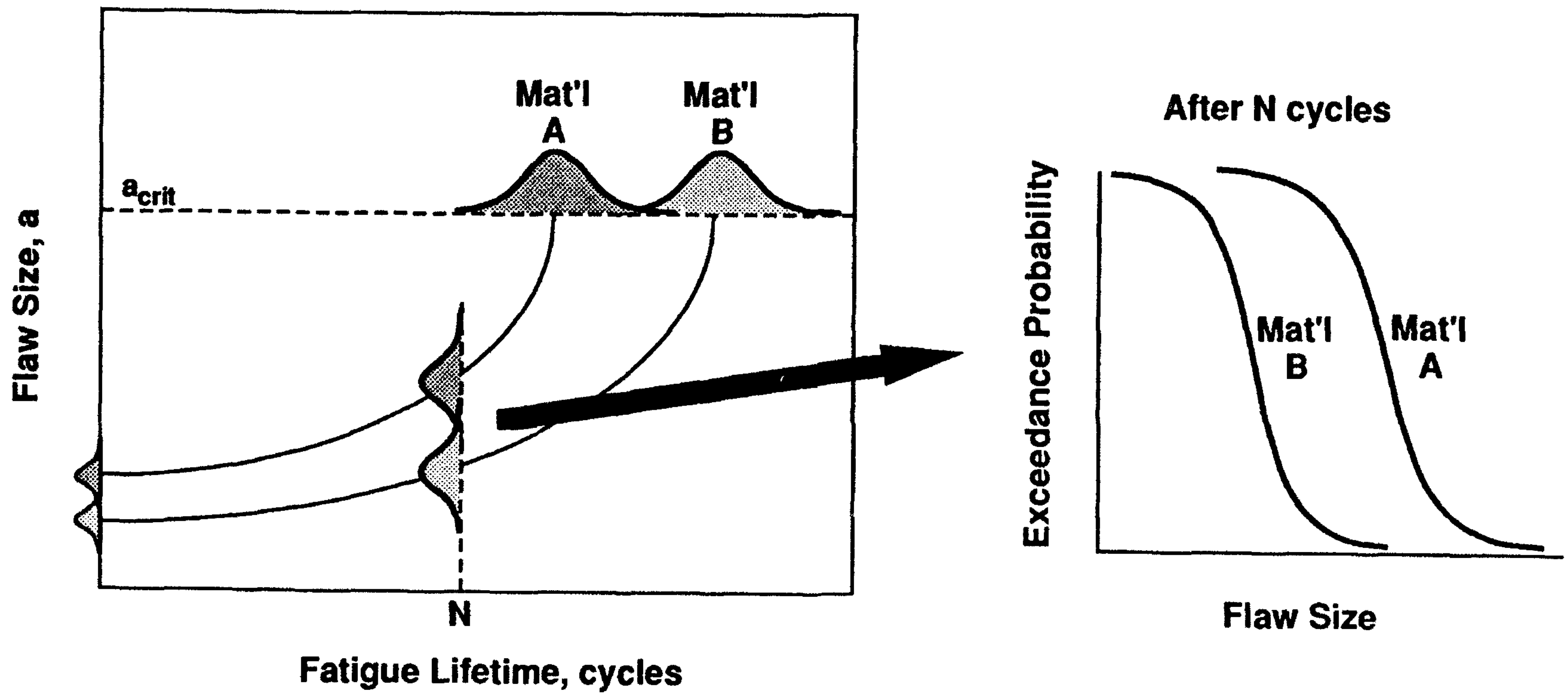

Figure 2a. Schematic representation of the flaw exceedance probabilities after a fixed lifetime for two materials with different intrinsic defect populations.

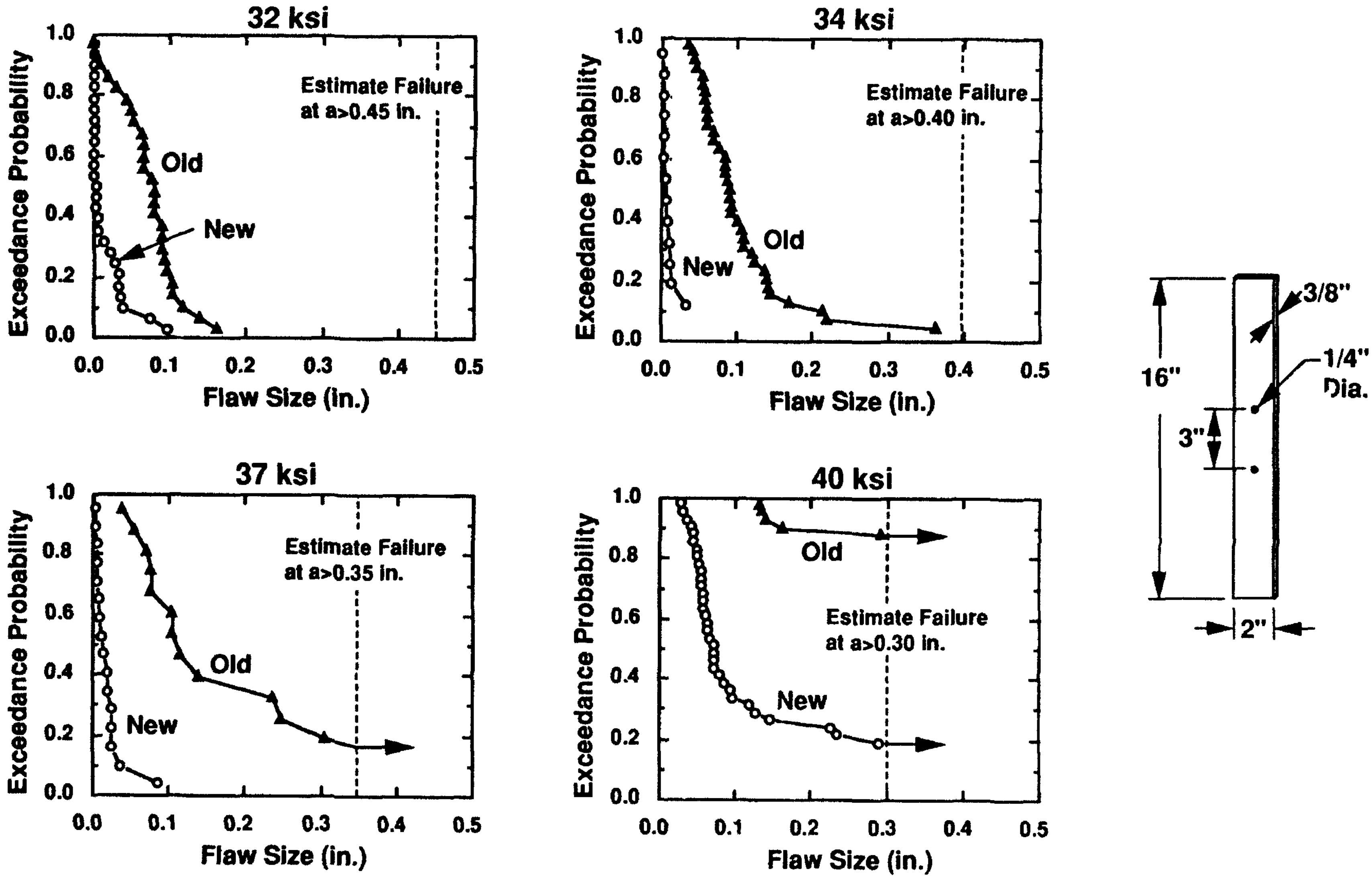

Figure 2b. Effect of 7050-T7451 thick plate quality on flaw size exceedance probabilities, T/2 specimen location, LT orientation, F-16 400 hr. lower wing spectrum loading, 16000 hrs. at spectrum peak stresses of 32, 34, 37, and 40 ksi. Test results courtesy of USAF [3].

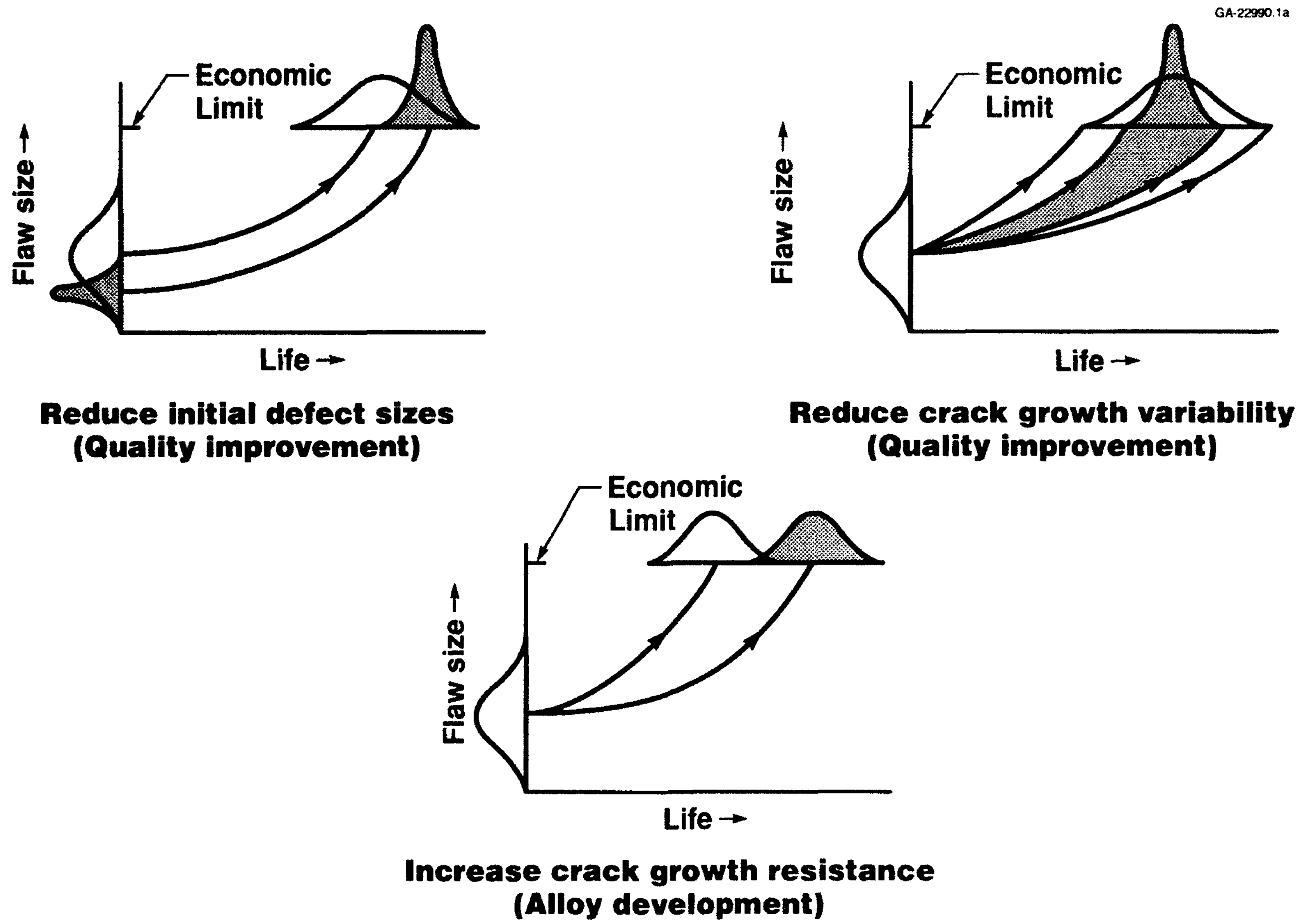

Figure 3. Materials and processing approaches to improving structural durability.

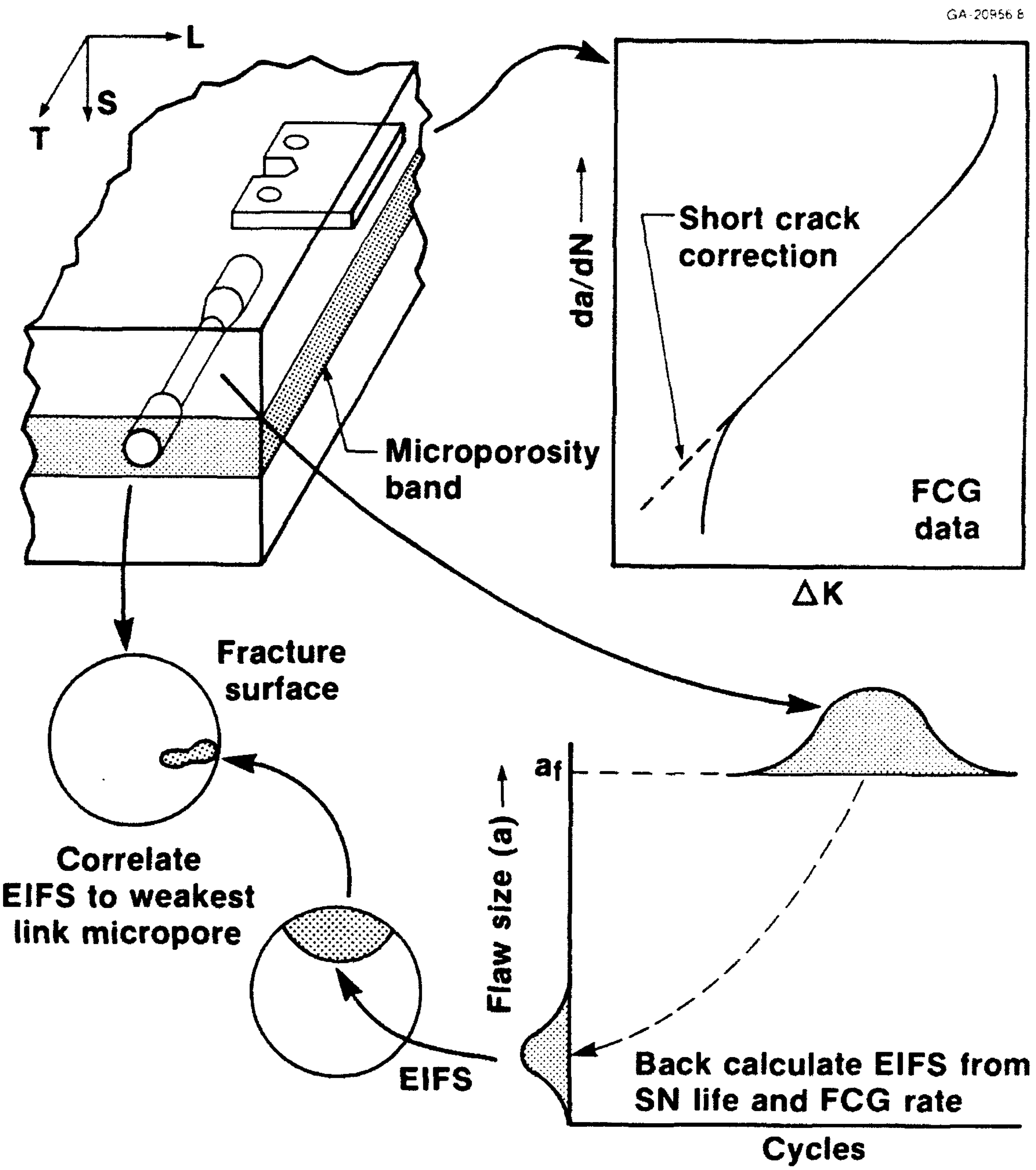

Figure 4. Analytical approach to obtaining material EIFS distribution.

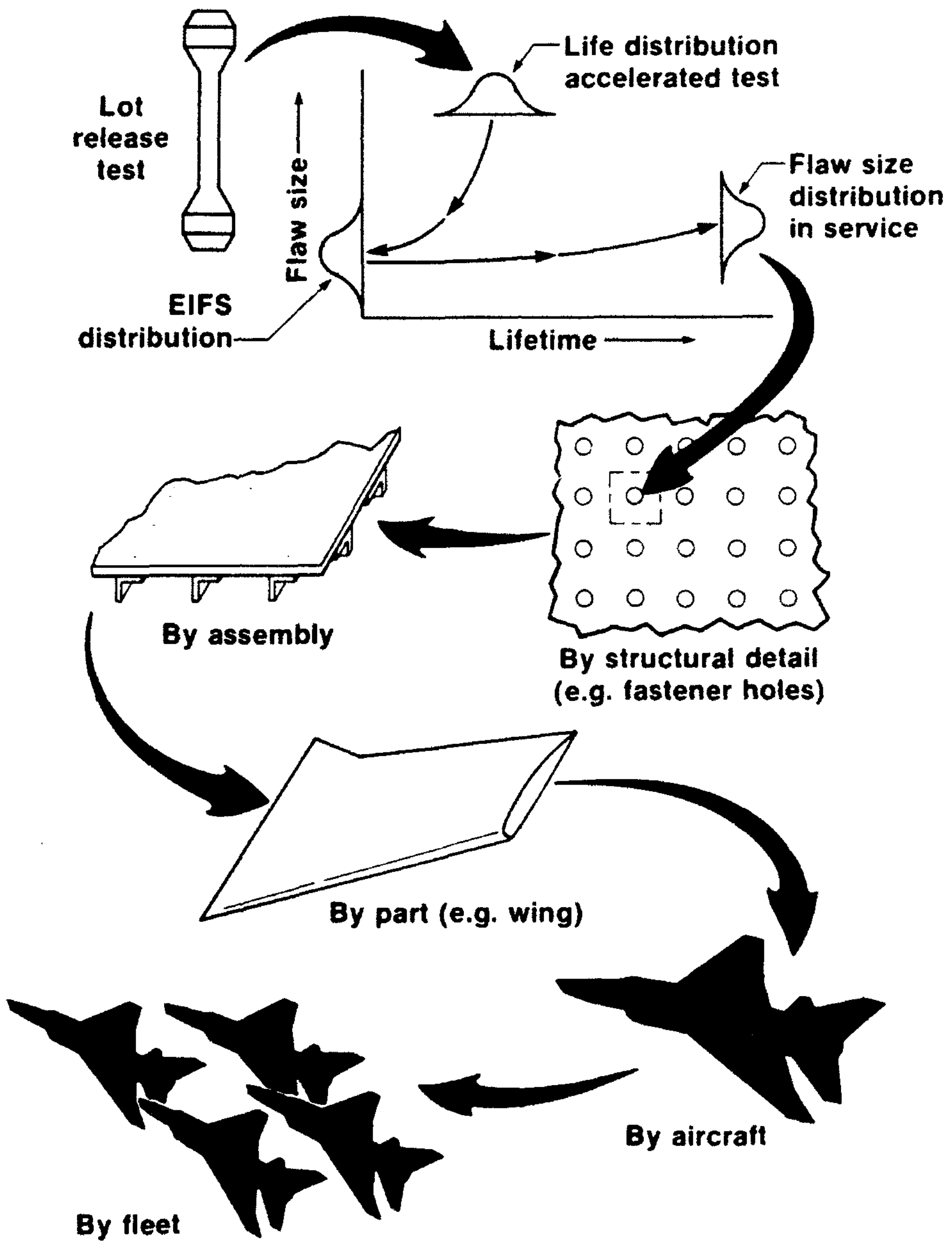

Figure 5. The use of EIFS distribution in life management at various structural levels.

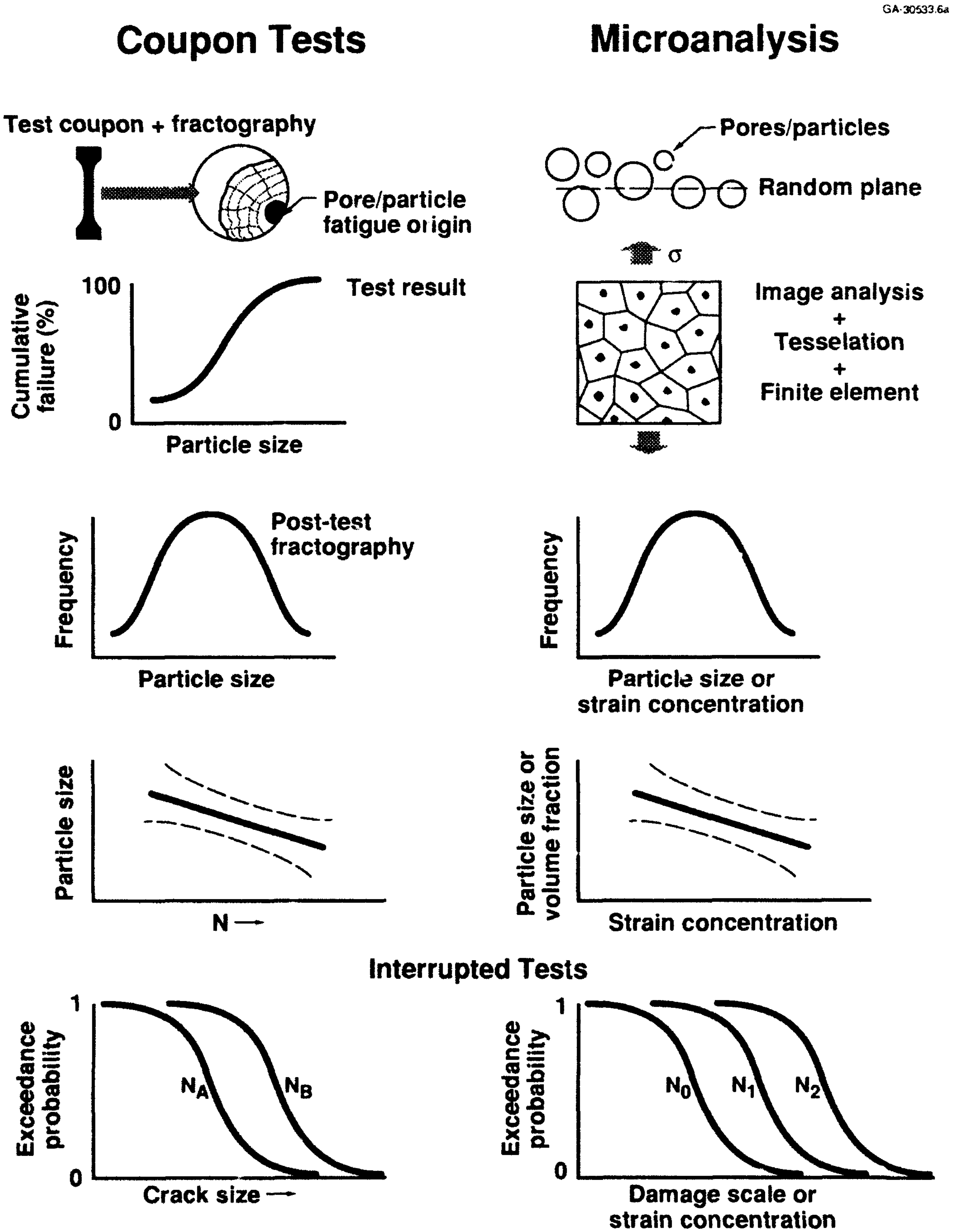

Figure 6. Corresponding linkages between test information and microanalysis.

Attachment 4

Projected and Actual Contract Expenditures